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Biophysical Evaluation of Footwear for Cold-Weather Climates

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Proper selection of footwear for cold-wet environments is important in determining individual performance and comfort. Testing only total dry insulation (It) is not a wholly adequate basis for boot selection. The present study demonstrates an effective method for evaluating the effects of surface moisture on boot insulation. This method allows a more knowledgeable selection of footwear for cold-wet climates. In this study, regional insulation values were obtained under dry conditions, then during a soak in shallow water, and finally for insulation recovery after removal from water. Results for seven boots show no advantage of presently used synthetic materials during short soak episodes. Insulated leather-synthetic boots, however, recovered to dry insulation levels more rapidly than more traditional insulated leather boots. Rubber waterproof bottoms were the most effective boot construction for retaining insulation levels during water exposure.

F OR INDIVIDUALS living or working in a cold climate, the selection of adequate hand- and footwear is a critical necessity. In response to long-term exposure to local environmental conditions, native populations have developed or adopted suitable technologies to protect the extremities (12). Modern industrial societies have tended to abruptly expose large populations of inexperienced, unacclimatized personnel to potential cold injury by uniformly equipping them with technical innovative, but frequently unrefined or inadequately field-tested footwear. These populations, once engaged in massive construction projects or military campaigns, are frequently restricted by supply limitations, organizational dogma, and task requirements to a

very narrow range of potential responses in the event that the footwear fails to provide adequate protection. Adequate footwear for the given task and environment is an important factor in the prevention of cold injuries (7). Industrial societies depend on laboratory testing to evaluate and refine designs rather than the conservative evolution of functional designs followed by native populations. The adequacy of laboratory testing procedures is, therefore, a crucial factor in the successful development and evaluation of new footwear designs.

At present the insulation of footwear in our laboratory is tested by mounting prototype boots over a standard cushion foot sock on a regionally heated copper foot model in an environmental chamber. Boot insulation is determined for each of 29 thermally isolated regions which correspond to sections of the model. Until very recently, only the weighed value for total insulation, I_t, was used as the criterion for comparing the insulation of different boots. The regional distribution of insulation however, may be a more important design feature of cold weather clothing than I_t. The dry insulation values for each individually heated section of the foot model and selected zones, such as combined heel and toe, serve as descriptors of efficiency of footwear in guarding against cold injury.

Current test methods examine footwear insulation only under dry conditions. On the basis of dry insulation values attributed to thickness alone, a papier-mache boot theoretically would provide adequate cold weather protection. However, the most difficult climate for cold weather footwear selection is the cold-wet condition where surface moisture often is absorbed into the insulating materials, thereby significantly reducing protection from cold injury. The criterion for determining if a particular boot provides adequate cold weather protection must be the amount of effective insulation under anticipated field conditions. The purpose

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of this paper is to show a new method for evaluating footwear which allows one to make a realistic evaluation of the functional insulation in footwear under wet conditions.

MATERIALS AND METHODS

The basic test procedure employed was to mount a commercially available, water resistant, vapor permeable (poly-tetrafluoroethylene (PTFE) base) sock over the sectionally heated copper foot (Fig. 1) to waterproof the model. A standard military cushion sock was placed over the PTFE sock. The boot was then tightly laced over the sock. A screw jack was used to apply a pressure of 70 kg against the bottom of the foot to simulate compression of insulation while walking. The insulation value of the boot was derived from measurement of the power demand required to maintain a constant temperature in each of 29 thermally isolated sections. This test procedure is essentially our standard method for evaluating footwear insulation and is an adequate method for comparing the dry insulating value of different boots. The boot was then placed in a plastic pan holding 5 cm of water and the test repeated. The boot was then removed from water and placed in the chamber under the same conditions as the initial dry run.

The test environment was an environmental chamber with automatic control. The box was set for an air temperature of 2°C, 50% relative humidity and an average air movement of 0.3 ms⁻¹. The surface of the copper model was controlled at 30°C. The tests were run in the cold chamber rather than in an open laboratory to have replicable, controlled conditions and because condensation is a function of humidity and temperature. In a colder environment, water evaporated at the 30°C model surface may recondense as it comes in contact with the colder boot shell or air. Also during the recovery phase, drying will be slower in a colder environment because less "environmental" heat is available to provide the energy for the phase transition from liquid to vapor and in terms of absolute water content the saturation capacity of cold air is less than warm air.

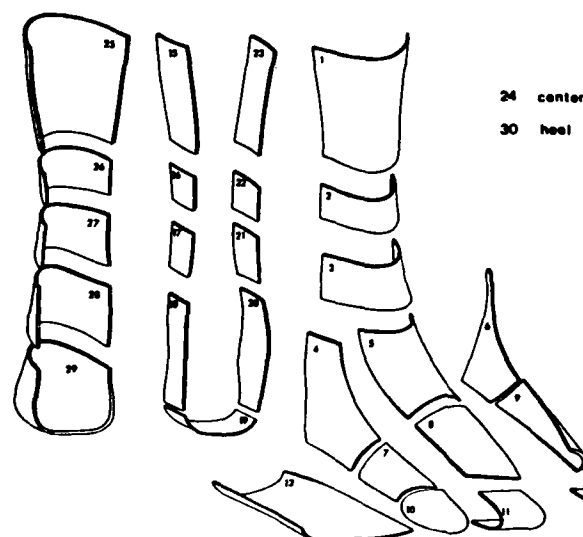The insulation values for each section were calculated

Fig. 1. Location of thermally isolated regions of the copper foot model.

every half hour by an internal program on a Hewlett-Packard 236 micro-computer control and data acquisition system. The basic formula utilized the area of each model segment (A_i, m²), the power (P_i, W) and the temperature gradient (ΔT, K) between the model surface and the chamber ambient used to calculate the local resistance (R_i) to heat exchange according to the following equation: $R_i = A_i \Delta T / P_i$. I_t was calculated as a weighted average, utilizing the A_i as the weighting factor.

The duration of water exposure and recovery periods varied during this study because the primary purpose was to develop the method rather than specific results. Initially, boots were kept in the soak phase until the I_t value plateaued. When our initial results indicated that for some boots, insulation values continued to drop after more than 30 h of soaking, it became apparent that for several boots, the time required to reach a stable level of wet insulation was in excess of realistic exposure time. After several tests, a uniform wet exposure of 7 h was selected. The recovery duration was variable but was at least a minimum of 7 h. After the initial tests, all tests were conducted with the pan of water in place but containing water only during the soak phase.

The boots tested include two low-cut warm weather hiking boots. One of these two boots has a vapor permeable laminated (PTFE) lining. The leather-synthetic boot tested has a similar lining plus microfiber insulation. The leather combat and leather cold-weather boots were military prototypes finished with a silicon based leather treatment. The shoepac is a military prototype based on a commercial design. In 5 cm of water, only the lower waterproof "foot" of the shoepac was in direct contact with the water. The mountain boot is a current military issue combination climbing-ski boot subjected to repeated testing. All other boots were in new conditions.

RESULTS

Table I shows the results for short term (7 h) exposure from tests of 7 different boots for total insulation, the boot sole (section 13), and the combined heel and toe regions (sections 10–12, 29).

Fig. 2 and 3 present the soak-recovery cycle for the leather cold-weather boot and the leather-synthetic boot, respectively. Standardized values were calculated by dividing the difference between the initial dry insulation value and each observed value by the initial dry value.

The total length of the soak period was 31 h for the leather boot and 23 h for the leather-synthetic boot. In the heel and toe region of the boots, Fig. 2 shows a plateau, whereas Fig. 3 displays an abrupt shift in the rate of insulation decrease near the end of the soak period. That shift may indicate a threshold to water resistance. Long-term recovery of insulation after removal of the boot from water is clearly slower for the leather boot. A comparison of the recovery of only the I_t values does not demonstrate the differences between the two boots as clearly as a comparison of the values for the sole or heel and toe regions.

The heavily insulated rubber-bottomed shoepac rapidly reached a stable low value for the same sections and I_t as shown for the cold-weather leather boot and the synthetic-leather boot. Those data, when plotted on the same scale as Fig. 2 and 3, demonstrate virtually no vertical displacement

TABLE 1. INSULATION VALUES FOR 7 BOOTS DRY, SOAKING IN 5 CM WATER, AND RECOVERING AFTER REMOVAL FROM WATER: TEST RESULTS.

Boot type	Region	Dry insulation (m²·K/W)	Insulation after 7 h soak (m²·K/W)	Percent decrease	Insulation after 7 h recovery (m²·K/W)	Percent recovery
Insulated leather synthetic boot	Total	0.209	0.191	9	0.185[a]	88
	Sole	0.259	0.206	20	0.216	83
	Heel & toe	0.205	0.167	18	0.163	80
Hiking boot with PTFE	Total	0.188	0.172[b]	8	0.177	94
	Sole	0.268	0.209	22	0.233	87
	Heel & toe	0.200	0.160	20	0.176	88
Hiking boot (2 runs)	Total	0.197	0.164	17	0.171	87
	Sole	0.254	0.180	29	0.212	84
	Heel & toe	0.197	0.140	29	0.164	84
Leather combat boot (2 runs)	Total	0.192	0.180	7	0.186	97
	Sole	0.260	0.202	23	0.242	93
	Heel & toe	0.186	0.160	14	0.181	98
Leather cold weather boot	Total	0.203	0.191	6	0.181[c]	89
	Sole	0.265	0.194	27	0.177	67
	Heel & toe	0.225	0.197	12	0.180	80
All leather mountain boot	Total	0.163	0.126	23		
	Sole	0.310	0.140	55	—	—
	Heel & toe	0.200	0.164	18		
Shoe pac with felt liner	Total	0.312	0.309	1	0.312	100
	Sole	0.338	0.327	3	0.338	100
	Heel & toe	0.310	0.302	3	0.312	101

[a] extended soak (23 h total)
[b] 5 hour soak
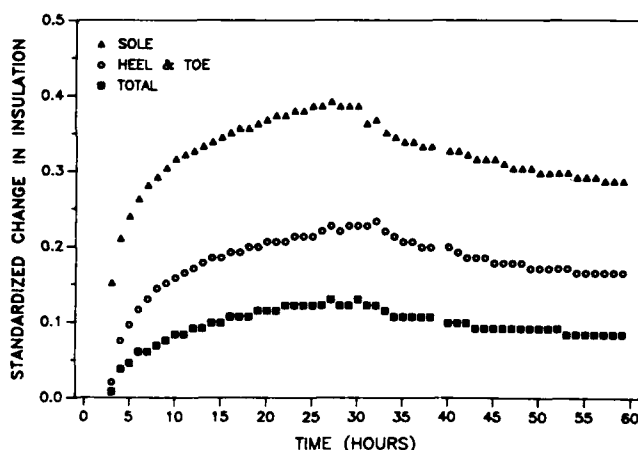[c] extended soak (31 h total)

Fig. 2. Standardized soak and recovery values (observed minus initial dry insulation divided by initial dry insulation) plotted against time for an insulated leather cold-weather boot.
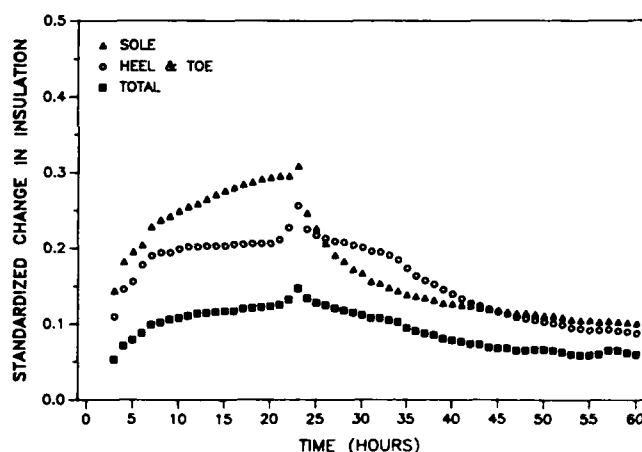

Fig. 3. Standardized soak and recovery values plotted against time for an insulated leather-synthetic boot.

and consequently the plot was not included in the analysis of this paper. The loss in insulation for the shoepac reflected only an increase in heat loss to a liquid substrate. A rapid recovery to original dry insulation values occurred because no moisture is absorbed into the boot. The results reflect the different response of different boots to a uniform environmental "challenge," 5 cm of still water. The contrast between the shoepac and the boots in Fig. 2 and 3 readily shows the advantage of waterproof boots over boots that absorb moisture when exposed to external moisture. These results reflect an advantage of footwear with completely waterproof bottoms that one would expect to experience in the field.

DISCUSSION

The problems associated with cold-weather footwear are related to insulation, ventilation, bulk, foot support, and traction (6). At the end of WWII, there were three general categories of cold weather boots available: porous, all-leather boots, fully waterproofed boots, and combination "shoe-pacs" with waterproof rubber bottoms and porous leather uppers. Supplemental insulation consisted of sheep shearling or wool felt. By 1944, the techniques behind the "vapor barrier" boot, which sandwiched a thick layer of insulation between two waterproof layers, were being developed (9). That level of boot technology was fully developed during

the Korean conflict and eventually became available to the civilian market.

Each of the three basic footwear types has advantages and short-comings. The porous, all-leather boot has adequate ventilation but absorbs surface water, thereby decreasing insulation unless the leather is specially treated. Leather treatment to increase water resistance may reduce the ventilation by blocking natural pores and/or deteriorate as the boot is worn. The leather itself may deteriorate with continued exposure, and when removed from contact with moisture the recovery of the insulation value is relatively slow. The fully waterproof boot has poor ventilation, less flexible materials, and if wear causes a puncture in the waterproof layer(s) water may actually become trapped inside the boot or in the interstices of the insulative material. The porous-waterproof combination shoepac combines advantages and disadvantages of the other two boot types. The shoepac is generally more durable than the all-rubber boot, more flexible, and has better ventilation. However, if water penetrates the porous leather uppers it may become trapped in the bottoms and the fit is not as good as leather boots. Except in extreme cold, wearers are likely to encounter some surface water deeper than the boot tops, but the frequency of such events is dependent on the locality.

The criticisms of each of the three basic boot types are based on footwear constructed from the materials available during WWII. New synthetic materials have become available for footwear manufacture since WWII. Synthetic uppers are not as susceptible to deterioration from repeated soaking. Water-resistant but vapor permeable fabrics may allow ventilation without absorbing water. Some synthetic insulating fibers may retain most of their insulating qualities when wet and micro-fibers may reduce the bulk of insulation. Other new insulation types include various plastic foams and synthetic pile. New plastics may produce a more durable and waterproof shell. The potential value of such innovations in footwear materials for wet-cold climates has not been effectively determined because present test procedures cannot wholly evaluate the effect of surface moisture on footwear insulation.

The selection of test exposure condition is important. Under cold-wet climatic conditions surface moisture exists in the form of precipitation, snow, streams or standing water. The level of exposure to environmental moisture depends on the individual's occupation. For example, military personnel routinely ford small streams, march through mud, standing puddles or snow, then bivouac or occupy field fortification under wet conditions. If exposure of the outer footwear surface to moisture is of sufficient duration, maximum moisture saturation of the boot materials will occur. Maximum environmental exposure can be simulated by submerging the boot in water until total saturation of the footwear materials occurs. Such worst case tests fail to distinguish between boot materials with differing rates of water absorption. Although situations exist in which individuals have worn footwear continuously for several days in standing water, a more realistic general field test is to expose footwear to shallow water for a shorter duration. Too short an exposure however will only discriminate between very porous materials and more resistant footwear.

The recovery of insulation after removal from contact with surface moisture is also important. In theory, the rate of absorption should be equal to the rate of recovery. The actual situation may be a breakdown of resistance to water penetration through the outer layer which is not readily reversed because the moisture becomes trapped in the insulation or inside the boot (1). As the boot dries the resistance to water penetration may recover, trapping moisture inside the boot. Furthermore, a small leak that was sufficient to admit water may be insufficient to allow complete drainage or enough ventilation to dry the inner boot, sock, or insulation.

One primary consideration in testing footwear is that very few features of basic design, construction or materials are consistent. Boots vary in sole thickness, height of uppers, insulation, seam construction, insulation, materials and "waterproofing" treatments. The underlying rationale used to select the test conditions in the present study was to pragmatically establish a standardized environmental challenge to which all the boots were exposed. The objective in this study was neither to establish a worst case scenario nor to determine maximum performance limits. Boots selected on the basis of worst case testing leads to overengineering. Test conditions could be adjusted to individual boots, but the ultimate question is how different boots will perform in the same environment. In evaluating the test conditions, the final consideration is whether the selected parameters induce stress on the boots that realistically simulates field conditions.

The dynamics of walking create additional stresses on the seams and materials of the boots which may affect the entry of moisture into the boot. The dynamics of movement probably affect elastic, porous materials as the compression and relaxation of movement alter the air spaces of insulating materials or the stresses on seams. Splashing through a mud puddle or shallow stream is a different situation from standing quietly in still water. No one knows how closely dynamic, very short term exposures, like the above scenarios, are equivalent to standing quietly in the same puddle, if in fact such situations can be compared. Our foot model was designed for static determination of insulation. We apply pressure to simulate static compression and it may be possible to generate waves or other turbulence in the water basin, but we would still not be adequately replicating the full effects of movement on the boot. Several laboratories, including the U.S. Army Natick Research, Development and Engineering Center (Natick, MA) have developed physical models that attempt to replicate the effects of motion on boot water resistance and wear, but no existing model can simultaneously measure the boot's heat exchange.

The hiking boot with the laminated waterproof, vapor permeable layer retained a higher percentage of the original dry insulation. The difference is essentially marginal for the two boots tested. It should be emphasized that the two hiking boots were dissimilar in terms of weight, leather thickness and general construction, so direct comparisons are questionable. The use of a PTFE lining may prevent water penetration from the outside environment, thereby protecting the insulating value of clothing layers inside the barrier; however, wet outside layers may reduce the effectiveness of vapor permeation by lowering the water vapor concentration gradient between the internal and external environment (4).

In previous footwear evaluation, boots that had I_t values

that varied 10% or less were considered to offer equal protection from heat loss under conditions equivalent to the test conditions. Based on those criteria and the results in Table I for dry I_t, five of the seven boots should provide nearly equal protection. It might be assumed that boots which have "equivalent insulation" would provide equal protection from the cold. However, cold injury tends to affect the extremities of the foot first (2,5). In addition, the sensation of discomfort under cold conditions is associated primarily with the foot region (3,10). Hence, both the wearer's perception of cold and susceptibility to cold injury are likely more dependent on local levels of insulation than the overall insulation (I_t) of the boot. Equivalent cold protection should mean that the insulation is equal for the critical regions in the two boots, not simply that their weighed I_t values are equal. A well designed boot with insulation concentrated in the regions of greatest heat loss potential can provide better thermal protection than a boot with poorly distributed insulation but a higher I_t.

Of the five boots which would be equivalent on the basis of I_t alone, in terms of heat loss from the heel and toe regions under the initial dry conditions, the leather cold weather boot we tested had the highest insulation value and only the leather-synthetic boot was within the 10% range of equality. When the insulation values at the end of a 7-h soak period were compared, the leather boot exceeded the 10% margin over the other four boots. If, however, the recovery of insulation is determined to be an important criterion, the most desirable boot may not be a leather boot. Under all of the conditions tested, the shoepac's insulation was the heaviest and best protected.

In an actual field situation, more is involved in the prevention of cold injury to the foot than just insulative properties of the boot. Different types of socks with moisture transmission ("wicking") properties or greater retention of insulation when wet or damp, sweat accumulation, proper foot care, and opportunities to remove footwear and dry both feet and footwear are also factors which determine the potential for cold injury (11).

Although limited, the test procedures employed in this study sought to simulate the effects of moderate levels of external moisture which affect the insulation in footwear. The shoepac performed better than leather boots primarily because the waterproof bottoms prevented insulation loss due to water penetrating the insulation. The insulation in water resistant leather boots was not reduced more than the insulation in boots constructed with synthetic materials after a 7-h soak. In a more severe test, with the boots completely filled with water and saturated, (as would occur, for example, in a large stream crossing) use of synthetic materials may be more efficacious than more traditional insulated leather boots. Under similar environmental conditions, completely waterproof boots would simply trap moisture inside the boot. The rapid recovery of synthetic-leather boot regional insulation to nearly pre-soak levels is an important characteristic which must be considered if exposure to surface moisture is not a chronic problem. The effect of surface moisture on the cold weather protection afforded by different footwear varies with the nature of the exposure to moisture and the construction and materials of individual boots.

In summary, the results of this study showed that for new boots, silicone treated leather boots may perform as effectively as boots incorporating synthetic uppers if exposure to water is of relatively short duration. With wear, the leather treatment may deteriorate, resulting in less thermal insulation and thereby greater heat loss. Wear may also compress or shift the position of this insulation. If only boots in new condition are tested, a hidden assumption is that synthetic materials will not be as affected by normal wear. Insulative materials that are dependent on a particular spatial or geometric configuration may become less effective or even suffer a breakdown in function due to the cumulative effects of wear (8). One important military consideration is that long term storage can result in deterioration of both synthetic and leather products depending on both the storage conditions and the materials in the boots.

ACKNOWLEDGMENTS

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